Extragalactic Gamma Rays From Compton Interactions and Bremsstrahlung

12-1 COSMOLOGICAL GAMMA RAYS FROM COMPTON INTERACTIONS

We next take into account the cosmological effects in computing the extragalactic γ-ray spectrum from Compton interactions between cosmic-ray electrons and photons of the universal blackbody radiation field in intergalactic space. The local ($z = 0$) spectrum is given from equation (8–19) as

$$I_{c,0}(E_\gamma) = \tfrac{2}{3}\sigma_T c H_0^{-1} f(\Gamma)\,(mc^2)^{1-\Gamma}\,(3.6k)^{(\Gamma-3)/2}\,K_{e,0}\rho_{r,0} \times T_{r,0}^{(\Gamma-3)/2} E_\gamma^{-(\Gamma+1)/2} \qquad (12\text{–}1)$$

for Compton γ-rays produced by cosmic-ray electrons having a power-law energy spectrum of the form

$$I(E_e) = K_{e,0} E_e^{-\Gamma} \qquad (12\text{–}2)$$

We have shown that, under the conditions where equation (12–2) is valid over all redshifts from 0 to $z_{\max}$ and where electron energy losses other than those from the universal expansion are neglected, the transformation from $K_{e,0}$ to $K_e(z)$ is given by

$$\begin{aligned} K_e(z) &= K_{e,0}(1+z)^3(1+z)^{\Gamma-1} \\ &= K_{e,0}(1+z)^{\Gamma+2} \end{aligned} \qquad (12\text{–}3)$$

where the first factor of $(1+z)^3$ represents the density effect and the factor of $(1+z)^{\Gamma-1}$ represents the transformation of the power-law energy spectrum from a burst of relativistic cosmic-ray electrons occurring at $z_{\max} \geq z$.

Substituting equations (11–12), (11–13), and (12–3) into the general formula (9–22), we find

$$I_c(E_\gamma, z_{\max}) = I_{c,0}(E_\gamma) \int_0^{z_{\max}} dz\, \frac{(1+z)^\Gamma}{(1+\Omega z)^{1/2}} \qquad (12\text{–}4)$$

Under these conditions, the power-law form for the Compton γ-ray

spectrum is maintained but the cosmological flux is enhanced by a factor given by the integral over z in equation (12–4).

However, Brecher and Morrison (1967) showed that the true situation is not as simple as that given by equation (12–4) under the conditions when the high-energy end of the electron spectrum is steepened owing to energy losses from the Compton interactions themselves. Since the blackbody radiation density is proportional to $(1+z)^4$, electrons lose energy primarily from Compton interactions, with the energy loss rate given by

$$\left(\frac{d\gamma}{dt}\right)_c = -\frac{4}{3}\frac{\sigma_T c \rho_r}{m_e c^2}\gamma^2 = \frac{(1+z)^4}{\tau_0}\gamma^2 \tag{12–5}$$

with

$$\tau_0 \equiv \frac{3m_e c^2}{4\sigma_T c \rho_{0,\,r}} \simeq 7.7 \times 10^{19}\ \text{s} \tag{12–6}$$

The energy loss from the universal expansion is given by

$$\left(\frac{d\gamma}{dz}\right)_{\text{exp}} = \frac{\gamma}{1+z} \tag{12–7}$$

From equations (12–5) and (9–41), we obtain

$$\left(\frac{d\gamma}{dz}\right)_c = \left(\frac{d\gamma}{dt}\right)_c \left(\frac{dt}{dz}\right) = \frac{(1+z)^2\gamma^2}{H_0\tau_0(1+\Omega z)^{1/2}} \tag{12–8}$$

The two energy loss rate terms are equal at the critical energy, $E_c = \gamma_c m_e c^2$, where

$$\gamma_c = \frac{H_0\tau_0(1+\Omega z)^{1/2}}{(1+z)^3} \simeq \frac{256(1+\Omega z)^{1/2}}{(1+z)^3} \tag{12–9}$$

or

$$E_c \simeq 0.13\frac{(1+\Omega z)^{1/2}}{(1+z)^3} \quad \text{GeV} \tag{12–10}$$

For $E < E_c$, the electron spectrum maintains its power-law form since these electrons lose their energy through the universal expansion; equation (12–3) is therefore valid. However, for $E > E_c$, the equilibrium electron flux is given by the solution of equation (7–24) under the conditions when Compton losses dominate. Under these conditions, equation (7–24) reduces to the form (Brecher and Morrison, 1967)

$$\frac{\partial}{\partial\gamma}\left[K_e\gamma^{-\Gamma'}\frac{(1+z)^4\gamma^2}{\tau_0}\right] = k_q\gamma^{-\Gamma} \tag{12–11}$$

where $k_q\gamma^{-\Gamma}$ is the original (injection) electron spectrum and Γ' is the exponent of the resulting equilibrium electron spectrum. It follows from

equation (12–11) that

$$\Gamma' = \Gamma + 1 \tag{12–12}$$

and

$$K_e = \frac{k_q \tau_0}{\Gamma (1+z)^4} \tag{12–13}$$

so that the equilibrium electron spectrum is depleted by a factor proportional to $(1+z)^4$ by Compton interactions with the universal radiation field and, in addition, the exponent of the electron spectrum is steepened by one power of E_e.

This steepening in the electron spectrum corresponds to a change of $\frac{1}{2}$ in the exponent of the Compton γ-ray spectrum at an energy

$$E_{\gamma, c} = \left\langle \frac{4}{3} \epsilon_0 \right\rangle \gamma_c^2 = 33 \left[\frac{(1+\Omega z)}{(1+z)^5} \right] \quad \text{eV} \tag{12–14}$$

Thus, the Compton γ-rays are expected to be produced by the steepened electron spectrum at all γ-ray energies. From equation (12–13), Brecher and Morrison conclude that unless there is a large evolutionary factor in the electron production spectrum, i.e., $k_q \sim (1+z)^m$, where $m \gtrsim 4$, there will be no significant enhancement of Compton γ-rays at large redshifts over those produced at the present epoch.

12-2 COSMOLOGICAL GAMMA RAYS FROM BREMSSTRAHLUNG INTERACTIONS

The local γ-ray spectrum from relativistic bremsstrahlung interactions is given by equation (8–36) as

$$I_{b,0}(E_\gamma) = 3.4 \times 10^{-26} n_0 c H_0^{-1} \frac{I_e(E_e > E_\gamma)}{E_\gamma} \tag{12–15}$$

Making use of equations (9–22) and (12–3), we obtain for the cosmological bremsstrahlung production spectrum

$$\begin{aligned} I_b(E_{\gamma 0}, z_{\max}) &= \frac{3.4 \times 10^{-26} n_0 c H_0^{-1} K_{e,0}}{\Gamma - 1} \\ &\quad \times \int_0^{z_{\max}} dz \, \frac{(1+z)^3 (1+z)^{\Gamma+2} [(1+z) E_{\gamma 0}]^{-\Gamma}}{(1+z)^4 (1+\Omega z)^{1/2}} \\ &= \frac{3.4 \times 10^{-3} \Omega}{\Gamma - 1} K_{e,0} E_{\gamma 0}^{-\Gamma} \int_0^{z_{\max}} dz \, \frac{(1+z)}{(1+\Omega z)^{1/2}} \\ &= \frac{6.8 \times 10^{-3}}{\Gamma - 1} K_{e,0} E_{\gamma 0}^{-\Gamma} \left[\left(1 + \frac{z}{3} - \frac{2}{3\Omega} \right) (1+\Omega z)^{1/2} \right. \\ &\quad \left. - \left(1 - \frac{2}{3\Omega} \right) \right] \end{aligned} \tag{12–16}$$

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In particular, for the Einstein-de Sitter universe where $\Omega = 1$,

$$I_b(E_{\gamma 0}, z_{\max}) = \tfrac{2}{3} I_{b,0}(E_{\gamma 0})[(1+z_{\max})^{3/2} - 1] \qquad (12\text{–}17)$$

and for the low-density model where $\Omega z \ll 1$,

$$I_b(E_{\gamma 0}, z_{\max}) = \tfrac{1}{2} I_{b,0}(E_{\gamma 0})[(1+z_{\max})^{2} - 1] \qquad (12\text{–}18)$$

Equations (12–16) through (12–18) are, of course, valid only in the energy range $E_\gamma < E_c$, with $E_c(\Omega, z)$ given by equation (12–10) corresponding to the energy range for electrons where they are undepleted by Compton interactions over a time scale corresponding to the age of the universe at a redshift z.

Stecker and Silk (1969), using a galactic cosmic-ray electron flux (Tanaka, 1968) given by

$$I_g = 1.26 \times 10^{-2} E_e^{-2.6} \qquad (\text{cm}^2\text{-s-sr-GeV})^{-1} \qquad (12\text{–}19)$$

have calculated the ratio I_0/I_g, where I_0 is the present flux of extragalactic electrons needed to produce the observed flux of isotropic γ-rays in the 0.1- to 1-MeV energy range under the assumption that these γ-rays are produced as the result of bremsstrahlung of extragalactic cosmic-ray electrons. They also calculated the fluxes of extragalactic protons needed to produce by π^0-decay the γ-ray flux above 100 MeV of 1.1×10^{-4} $(\text{cm}^2\text{-s-sr})^{-1}$ originally reported by Clark et al. (1968).

The resultant γ-ray spectra from bremsstrahlung and inelastic strong interactions were calculated for two cosmological models (viz, an Einstein-de Sitter (flat) universe with $n_0 = 10^{-5}$ cm^{-3} and an open universe with $n_0 = 10^{-7}$ cm^{-3}) and three models of cosmic-ray production (viz, a burst model where all the cosmic rays were produced at some initial epoch, a constant leakage model where cosmic rays have leaked out of radio sources at a constant rate since $t(z_{\max})$, and an evolving source model as suggested by Longair (1966) where the cosmic-ray production rate varies as $(1+z)^3$). These models have been discussed previously in chapter 10. The characteristics of the γ-ray spectra from these various processes are outlined in table 12–1. The values of I_0/I_g obtained for extragalactic cosmic-ray electrons and protons are shown in figures 12–1 and 12–2. They are plotted as functions of $(1+z_{\max})$, as needed to explain the observations.

The cosmic γ-ray (or X-ray) spectrum from nonrelativistic bremsstrahlung interactions of electrons has been calculated by Silk and McCray (1969). They calculated the bremsstrahlung spectrum of nonrelativistic electrons by using equation (8–26), taking into account the energy losses of the lower energy electrons by coulomb interactions in calculating the equilibrium spectrum of extragalactic electrons as a function of redshift. Their resultant electron spectrum is shown in figure 12–3. Figure 12–4 shows their calculated X-ray spectrum together with some of the recent observations of isotropic X-ray fluxes.

TABLE 12–1.—*Characteristics of Predicted Extragalactic γ-Ray Spectra From Various Processes in Given Energy Regions*

	< 0.5 MeV	1 to 100 MeV	> 100 MeV
Compton	Power-law spectrum of form $E^{-\Gamma}$ where $\Gamma = (\beta+1)/2$ and β is the index of the cosmic-ray electron spectrum. In particular, $\Gamma=2.3$ for $\beta = 3.6$ as discussed by Felten and Morrison (1966).	$\sim E^{-2.3}$	$\sim E^{-2.3}$
Bremsstrahlung	Power-law spectrum of form $E^{-\Gamma}$ where $\Gamma = \beta$ and $\beta \simeq 2.6$ in an open universe.	Power-law spectrum of form $E^{-\Gamma}$, where $\Gamma = \beta$ and $\beta \simeq 2.6$. (See text.)	$\sim E^{-3.6}$
Inelastic strong interactions	Negligible contribution; power law of form $\sim E^{+\Gamma}$ where $\Gamma \simeq 3$.	Spectrum peaks in this energy region at $\simeq 70\ \mathrm{MeV}(1+z_{max})^{-1}$.	$\sim E^{-3}$
Annihilation	Power-law production spectrum of form $E^{-\Gamma}$, where $\Gamma \simeq 2.68$ for flat universe and $\Gamma = 3.18$ for open universe. Absorption effects become important in this energy range. (See ch. 13.)	Power law of form $E^{-\Gamma}$, where $\Gamma \simeq 2.86$ for flat universe and $\Gamma \simeq 3.36$ for open universe.	Power law becomes steeply falling spectrum with no flux above 919 MeV.

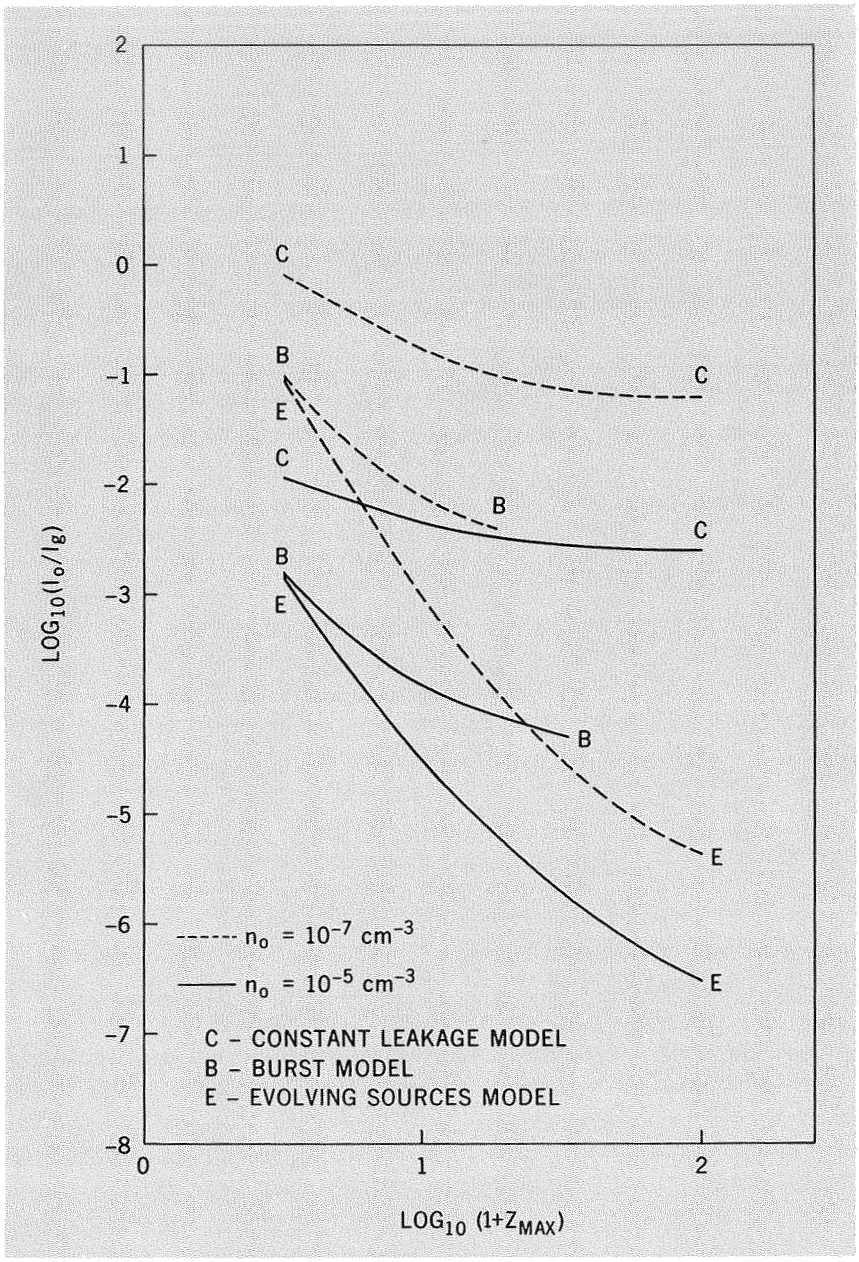

FIGURE 12–1.—Extragalactic electron intensities (Stecker and Silk, 1969).

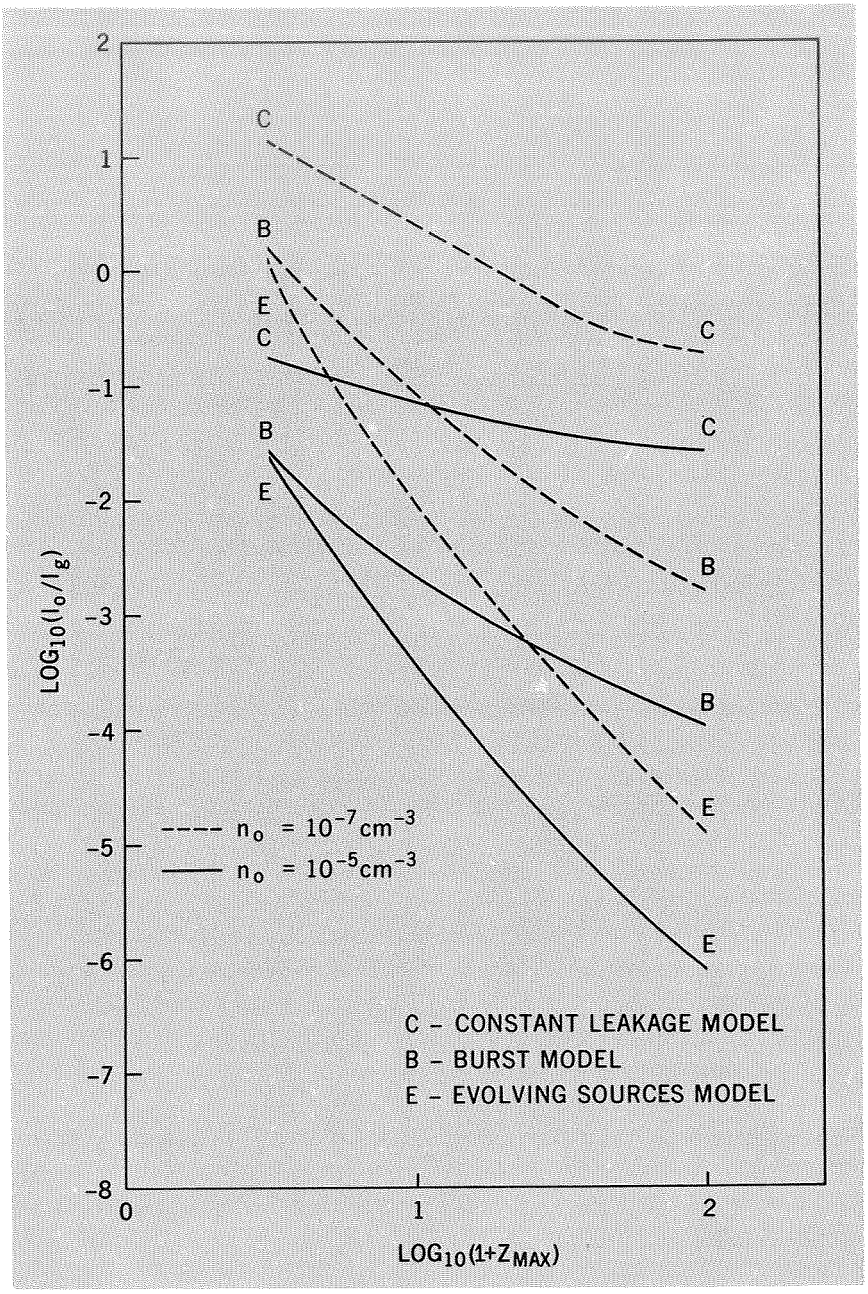

FIGURE 12–2.—Extragalactic proton intensities (Stecker and Silk, 1969).

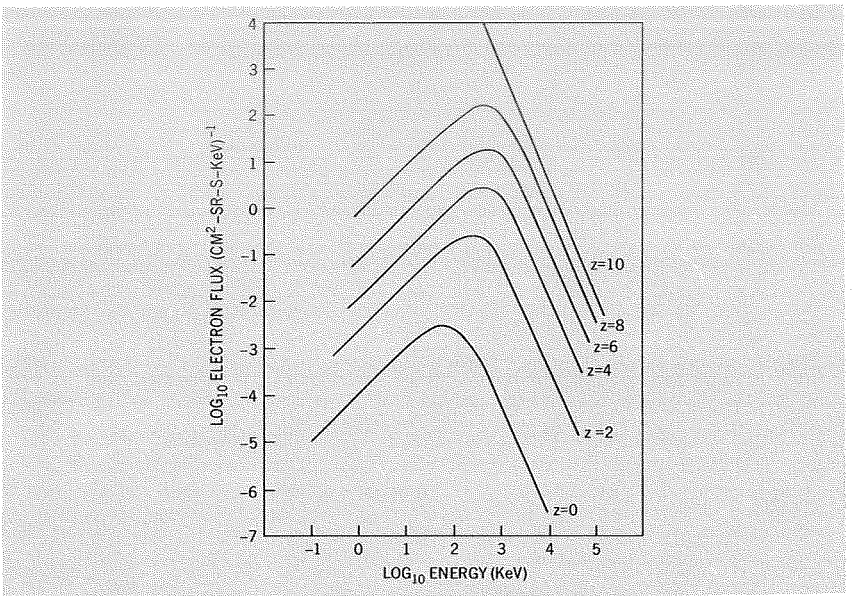

FIGURE 12–3.—Relaxation of a power-law cosmic-ray electron spectrum in an expanding universe with an ionized intergalactic medium ($n_0 = 10^{-7}$ cm^{-3}) (Silk and McCray, 1969).

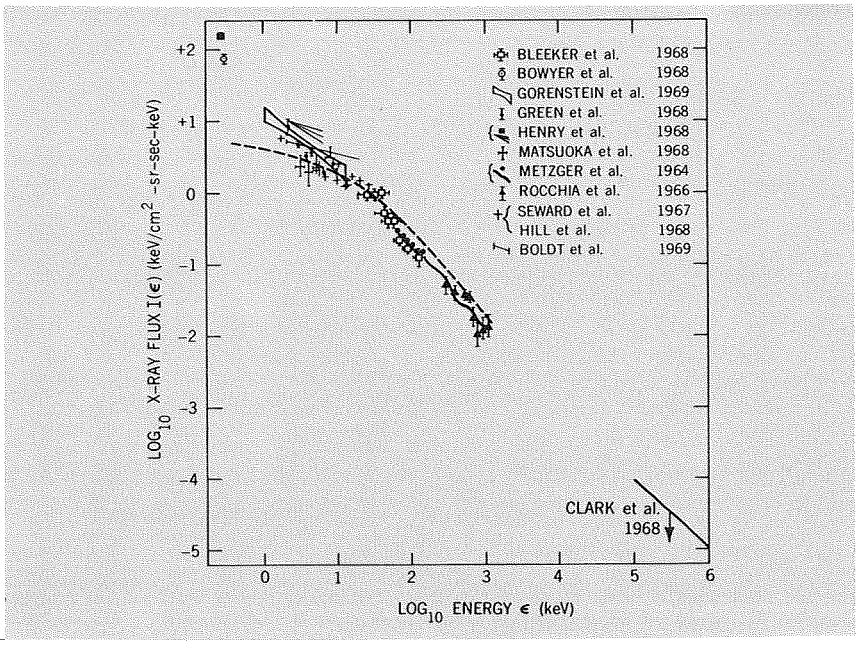
LOG10 X-RAY FLUX I(ϵ) (keV/cm2 -sr-sec-keV)
LOG10 ENERGY ϵ (keV)
BLEEKER et al. 1968
BOWYER et al. 1968
GORENSTEIN et al. 1969
GREEN et al. 1968
HENRY et al. 1968
MATSUOKA et al. 1968
METZGER et al. 1964
ROCCHIA et al. 1966
SEWARD et al. 1967
HILL et al. 1968
BOLDT et al. 1969
CLARK et al. 1968

FIGURE 12–4.—Diffuse X-ray observations compared with calculated flux from burst model (dashed curve). The 0.25-keV point of Henry et al. (1968) has no correction for interstellar absorption (Silk and McCray, 1969).